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Environmental design guidelines for residential NZEBs with liner tray construction

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ABSTRACT

Liner tray, steel gauge, or cassette construction is a lightweight steel frame system (LSF) especially suited for low-rise buildings, which offers celerity and quality. It is a viable option for constructing affordable residential Nearly Zero Energy Buildings (NZEBs) in those areas where 'craft-based' house-building industries have proven unsustainable, as occurs in some countries of Southern Europe. From an environmental point of view, the continuous disposition of liner trays allows excellent adaptability to the microclimatic context and the particularities of the local site as well as the thermal homogeneity of the envelope. However, its lightweight can entail large thermal variations and overheating problems, especially in constructions with high thermal resistance. A careful design adapted to each location can help avoid these problems, but accurate energy calculations are not always feasible in detached house design. This paper studies the Proyectopía system's passive strategies, an innovative liner tray system made of extruded aluminum for sustainable, low-cost detached houses in Spain. Environmental design guidelines can be a powerful and suitable tool for addressing various house projects that share the same construction system. Several parameters with a substantial impact on the house energy demand, such as insulation thickness, window glazing type, window-to-wall ratio, solar shading, and thermal inertia, are analyzed in a house prototype. Designers can use these parametric study results to perform environmental assessments from the early stages of the design process.

1. Introduction

Modular architecture is an exciting alternative to on-site construction, offering higher quality standards, reduced construction time, control of the costs, and potential for lower energy consumption, as explained in the scientific literature of recent years [1–8]. It is a booming field, with more presence in developed countries (Sweden 90%, Netherlands 50% and Japan 12–16%), being determinant causes the size of the housing industry, the consumer preference for new housing over renovations, and the public support [9]. However, residential construction industrialization has great potential in countries with 'craft-based' industries and low-efficiency housing, as in Southern Europe [10,11].

The Spanish construction sector has completed a phase of tremendous growth where any method of construction proved to be profitable, favoring lack of innovation, to a phase of stagnation where higher quality and sustainability have become a necessity [12,13]. Recent updates of national energy regulations seek to improve commitment to the Energy Performance of Buildings Directive (EPBD) in Spain (Basic Document outlining Energy Saving in the Technical Building Code, CTE-DB-HE-2019) by compelling new constructions to reach NZEB standards in 2020, a term to be fully defined by the Member States, with the Passivhaus standard as a reference [14]. The 20% energy efficiency target to be achieved by 2020 must reach 32.5% by 2030 [15] and energy inequalities within the same climate should be taken into account [16]. Sustainability refers not only to environmental aspects but also to economic and social aspects, with the second category being the most determinant regarding the choice of construction method, especially indicators "Design and construction time" and "Design and construction costs" [17].

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In such a way, the Spanish Institute for Industrial Technology Development (CDTI) supported the development of a liner tray system for the assisted design and construction of detached houses with low energy consumption and low cost, based on components of extruded aluminum that are easy to carry and assemble [18]. The research was done between 2015 and 2017 in Galicia, a territory in Northwest Spain with low-density residential areas, a high rate of detached houses, and limited access to sustainable dwellings.

Metallic structures in modular construction have many advantages, such as lightness, dimensional accuracy, and minimum maintenance requirements. It also has some disadvantages, such as low thermal inertia and high thermal conductivity, negatively affecting indoor thermal comfort [19,20]. Thus, attention to the environmental performance of buildings with metallic structures becomes especially relevant, which depends on the architectural design and the construction system [21].

LSF construction offers a wide range of systems that can be categorized into three main groups according to the nature of the prefabricated element: (1) stick-framing or stick-built, (2) panelized or areal, and (3) modular or volumetric, which can also mix into hybrid systems [22]. Generally, the smaller the prefabricated element is, the higher the design flexibility but, the longer the construction time. From an environmental point of view, systems stick framing (1), and panelized (2) lead to greater formal variety than the system volumetric (3). Thus, buildings based on systems (1) and (2) have higher adaptability to microclimatic contexts. Furthermore, system panelized (2) involves higher envelope homogeneity, which also means thermal continuity.

In category (2), there is a liner tray, steel gauge, or cassette system, which are C-shaped steel sections, usually of cold-formed steel and less commonly of aluminum. It is an innovative alternative to classic LSF constructions [23] with structural advantages [24,25] and good seismic behavior [26], and they involve higher productivity [27,28]. Davies [29] stated that this system's particular remarkable application is the vertical arrangement of the liner trays forming the load-bearing walls of low-rise constructions. When using liner trays of aluminum, the construction of the load-bearing walls is especially agile [30]

The Proyectopía construction system belongs to the panelized category (2), with subtype liner trays in continuous layout, where the metal liner trays are created from extruded aluminum, and they compose the load-bearing walls and roof. The result is a resistant metallic vault forming the dwelling's whole structure and two facades, implying a direct relationship between structure and form.

Heat gains and losses are defined by the building form, orientation, and envelope composition. Therefore, the construction potential for superior environmental performance is understood as low energy demand and indoor thermal comfort [31,32]. The construction system flexibility allows a wide range of building forms, favoring adaptability to project requirements and site conditions but hindering energy efficiency estimation. However, the fact that the constructive solutions are the same in all houses provides an excellent opportunity for developing reliable environmental design guidelines. Among the most relevant LSF design strategies are window glazing, thermal insulation, solar shading, natural ventilation, and thermal inertia [22,33]. The challenge is to evaluate their effectiveness for a great variety of house forms, plot shapes, and climate conditions. This paper explores the passive housing design strategies with the construction system Proyectopía in several Spanish locations, considering affordability and exportability.

2. Material and methods

The study is based on the environmental optimization of the dwelling prototype Proyectopía, located in Pontevedra, using as an indicator the total annual primary energy of useful building area kWh/m^2 defined by the Passivhaus standard (section 2). Parametric studies are carried out to calculate the impact of several design features on the prototype energy consumption and the prototype's adaptability to other climatic and urban contexts (section 3). Fig. 1 represents the methodology followed. The results are of use as a design guideline for LSF NZEB detached houses in Spain, and they may also serve as a basis for comparison with on-site monitoring of the Proyectopía built prototype.

2.1. Study case: proyectopía dwelling prototype

The system Proyectopía is based on modular load-bearing walls and roofs fulfilling both structural and envelope functions, comprising a multilayer panel of extruded aluminum, insulation, and wood depicted in Fig. 1. On the outside, the aluminum components (alloy 6082) are omega-shaped elements 300 mm wide and 90 mm thick that create a ventilated air gap (element 1 in Fig. 1). A textile sheet separates them for waterproofing and airtightness (2) from a wooden board 15 mm thick (3), followed by a layer of mineral wool of 100 mm (4), a layer of extruded polystyrene 70 mm thick, a vapor barrier, and a wooden board 15 mm thick (5), on the inside.

The facades, represented in Fig. 2, are nonstructural walls made of 2 mm of natural stone over a polystyrene board (element 11 in Fig. 2) on a wooden structure (12), attached to mineral wool 140 mm thick, with an inner wooden board (13). Furthermore, the windows have aluminum framing and triple glazing, partitions and ceilings are produced from oriented strand boards (OSBs), and the intermediate floor consists of wooden beams and OSB boards. Foundations are concrete slabs 30 cm thick over precast recycled polypropylene sections forming a ventilated chamber.

This system can be categorized as cold frame construction based on the internal position of the insulation. Although thermal bridges are identified on the beams connecting the two load-bearing walls and on the beams supporting the intermediate floor (facade section in Fig. 2), they have not been considered in the numerical simulations. In both cases, the u-shaped beam flanges interrupt the continuity of the first layer of thermal insulation, so they have not been considered critical. This type of thermal bridge can be classified as geometric, according to Soares [22].

The dwelling prototype Proyectopía is a representative home defined in the Neotec research project considering the surface, volume, and layout data of local housing. It is a two-story construction of plan dimensions 5.35 × 6.68 m and 2.50 m height and flat roof, with compactness factor 0.67 (S/V). It has narrow windows in the East and West load-bearing walls (named "A" in Fig. 3) and large glazing in the South and North facades (named "B" in Fig. 3), with window-to-wall ratios (WWRs) of 9.92%, 6.61%, 94.21%, and 53.2%, respectively. An open kitchen, living room, and toilet are situated on the ground floor, and two bedrooms and bathrooms are positioned on the first floor. Table 1 compiles the U-values of the main construction elements. The intermediate floor has been considered adiabatic.

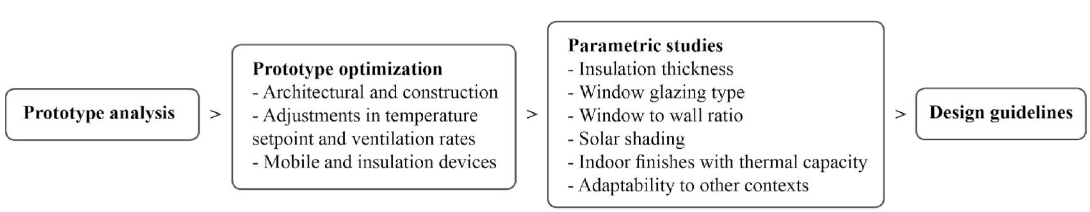

Fig. 1. Schematic depicture about the methodology followed.

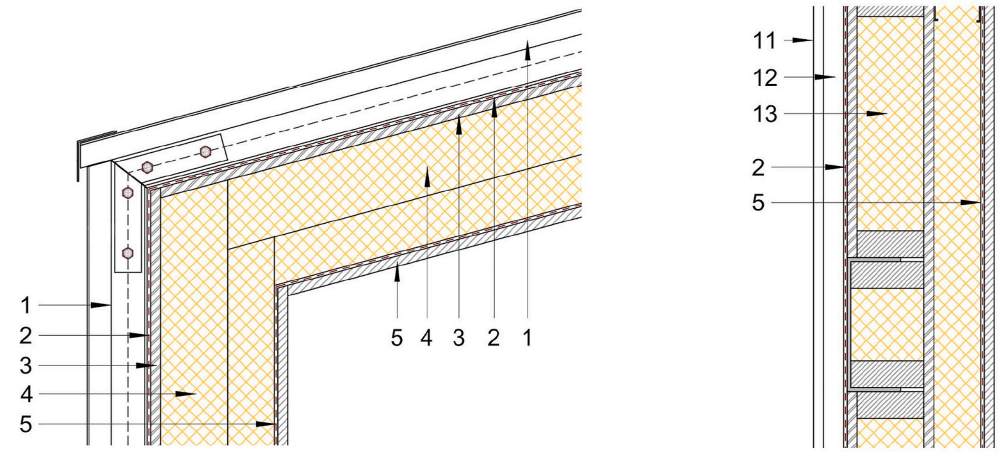

Fig. 2. Section of the modular load-bearing walls and roofs (left) and the facade section (right).

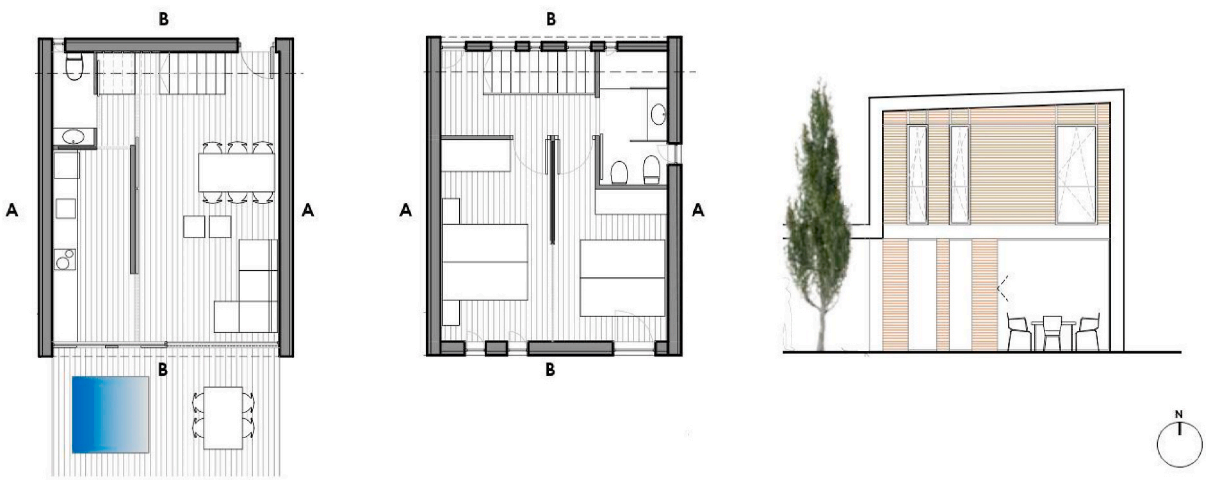

Fig. 3. Simplified blueprints of the prototype.

Table 1
U-values of the prototype main construction elements (W/m^{2}K).

Load-bearing walls	Facades	Roof	Foundations	Window glazing	Window frame
0.14	0.18	0.14	0.32	1.36	4.91

Energy certification based on the Basic Document outlining Energy Saving in the Technical Building Code, CTE-DB-HE, shows that the annual heating demand is 27.84 kWh/m^{2}y and the annual cooling demand is 20.65 kWh/m^{2}y. Advanced simulations run with Openstudio and EnergyPlus show further detail about the prototype's indoor comfort and energy profile. Geometric and energy models are built considering the characteristics described above, in addition to occupancy patterns and equipment schedules (Fig. 4). The Energyplus weather file ESP SWEC WMO# = 080440, in the location of Pontevedra (latitude 42.43, longitude −8.7 and elevation 840 feet), is used as a representative climate year according to past decades. Pontevedra has a warm-summer Mediterranean climate, Csb, according to the Köppen–Geiger climate classification system. It has mild winters, with the lowest monthly mean temperature of 9,9 °C registered in January and temperate summers, with the highest monthly mean temperature of 20,5 °C registered in August. These two months are selected for analysis of the main results. Reliable simulation tools become necessary to develop an accurate assessment of the dwelling design parameters, considering the LSF construction singularities [22].

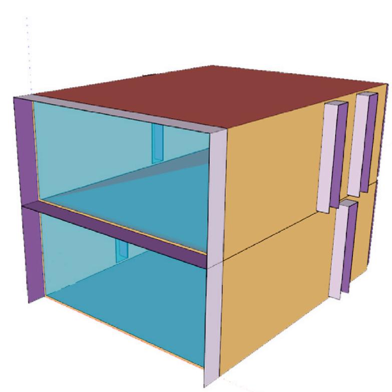

Fig. 4. View of the model used for numerical simulations.

The free-running simulation demonstrates that daily indoor temperature extremely varies all year long, having persistent overheating problems in summer and frequent overheating problems in winter. Fig. 5 presents August's indoor temperatures on the first floor, considered the worst-case scenario in terms of overheating. Fig. 6 shows indoor temperatures on the first floor in January. Considering an initial comfort band of 19°C–25 °C all year long and system activation all year long, energy loads would be significant every month of the year, and annual heating and cooling demand would go up to 122.93 kWh/m^{2}y

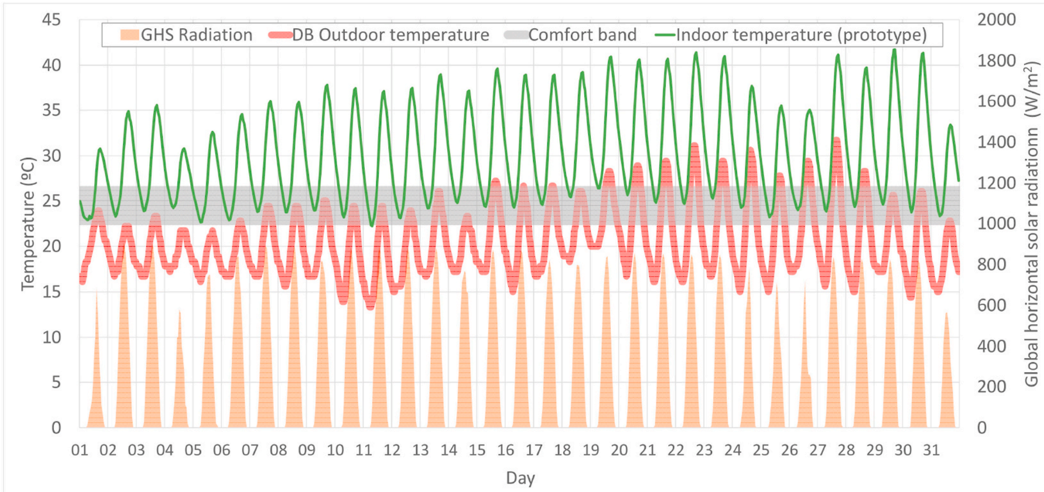

Fig. 5. Indoor temperature in August.

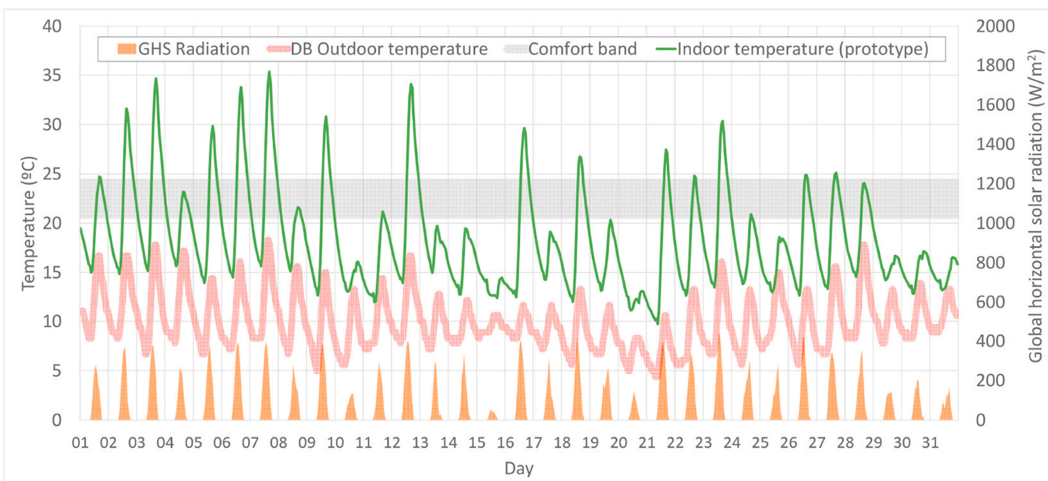

Fig. 6. Indoor temperature in January.

and 59.31 kWh/m^{2}y, respectively. Since the subject of this paper is passive design, consumption results are obtained as 'ideal conditioning loads,' disregarding equipment characteristics. The minimum ventilation rate (33 l/s) recommended by CTE over 24 h was considered.

Sections 1 and 2 graphs display indoor (colored thin lines) and comfort temperatures (gray band) related to the dry-bulb outdoor temperature (thick pink line) and global horizontal solar radiation (orange hatch).

2.2. Energy optimization of the dwelling prototype

2.2.1. Architectural and construction measures

Two initial design measures are taken to increase the dwelling energy efficiency. Window size reduction in the North Facade (window-to-wall ratio, WWR, from 53.2% to 20.10%) has a limited impact on energy consumption due to the window's high thermal resistance. However, the addition of overhangs on the South Facade makes summer maximum temperatures decrease by 3 °C.

Window glazing is a building feature with a considerable impact on environmental performance. Comparing the three glazing types for the prototype's current energy balance confirms that the lower window thermal resistance can contribute to narrow thermal variations (Fig. 7), helping avoid overheating problems (Fig. 8). Thus, glazing type 2 is adopted in the following simulations. Table 2 compiles the window glazing characteristics.

Solar shading can help achieve indoor thermal comfort in the summer without compromising it in the winter. Simulations run with 50 cm, 100 cm, and 120 cm overhangs show that large overhangs effectively reduce the highest indoor temperatures in the summer when the sun's altitude peaks. Consequently, 120 cm overhangs are implemented in the following simulations. According to the weather file, ESP SWEC WMO# = 080440, winter in Pontevedra is not severe, where 4.4 °C is the lowest temperature, and 9.9 °C is the average temperature in January. Reduction of thermal insulation thickness in load-bearing walls, facades, roofs, and floors from 20 cm to 10 cm barely affects energy consumption or indoor temperatures (Fig. 9). Ten centimeters of thermal insulation are considered in the subsequent simulations.

The use of indoor finishes with thermal storage capacity can help increase the building's thermal inertia, considerably improving indoor thermal comfort. The use of cement boards in walls, floors, or ceilings is an alternative that complies with the system philosophy, as it is a light material with dry assembly and moderate cost. Figs. 10 and 11 confirm that the use of a cement board with a density of 1200 kg/m^3 helps smooth indoor temperatures substantially. Maximum indoor temperatures decrease by 3 °C in the winter and 5 °C in the summer, and minimum indoor temperatures slightly increase. The use of cement boards on horizontal and vertical surfaces is adopted hereafter.

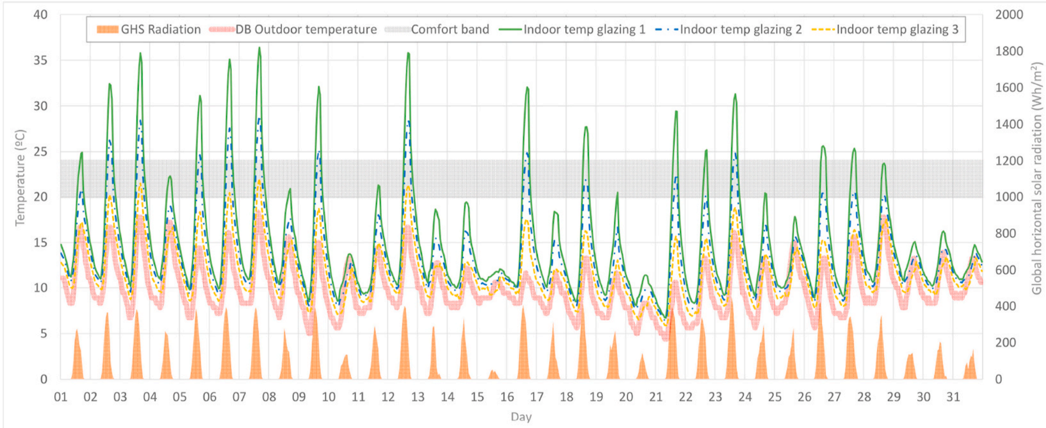

Fig. 7. Window glazing type comparison. Monthly indoor temperature in January.

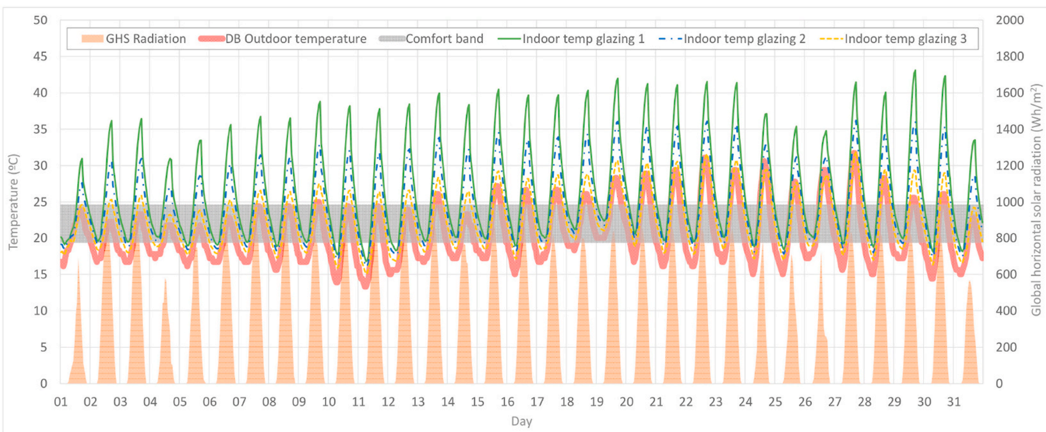

Fig. 8. Window glazing type comparison. Monthly indoor temperature in August.

Table 2
Window glazing characteristics.

	Window glazing type 1 (green)	Window glazing type 2 (blue)	Window glazing type 3 (yellow)
U-value (W/m^2K)	1.36	2.56	6.81
Solar heat gain coefficient SHGC	0.45	0.40	0.25

Overall, this group of measures reduced heating consumption by 68% to 38.51 kWh/m^2y and cooling consumption by 77% to 13.40 kWh/m^2y. The annual profile is now less steep, and conditioning seasons are more clearly marked.

2.2.2. *Adjustments in temperature setpoint and ventilation rate*

After this first series of measures, detailed thermal comfort analysis is carried out based on European standard EN15251, considering category II. Indoor comfort temperatures are calculated with respect to each month's average temperature, so the comfort band is variable throughout the year. The heating season is now limited to six months, from November to April, and the cooling season is narrowed to four months from June to September, negatively impacting heating consumption, which reaches 54.43 kWh/m^2y and positively affecting cooling consumption, decreasing to a low value of 0.86 kWh/m^2y.

Natural ventilation is a crucial aspect of the dwelling prototype performance. Previous simulations were run with the minimum ventilation rate according to the technical building code in the continuous regime or 33 l/s for 24 h. However, variations in ventilation rates profiting the highest outdoor temperatures within the day and throughout the year can improve energy efficiency. Higher ventilation in winter between 1 p.m. and 5 p.m. and daily summer ventilation between 10 a.m., and 10 p.m. reduced the heating demand to 26.20 kWh/m^2y and cooling loads to 0.63 kWh/m^2y.

Under the current conditions, enhancing window glazing can be positive. The use of window glazing type 1 can low heating consumption down to 12.05 kWh/m^2y, achieving the energy target, set at 15 kWh/m^2y.

2.2.3. *Mobile shading and insulating devices*

The use of mobile devices can provide buildings with adaptive tools to improve their performance. Window shutters used on cold nights and hot middays can effectively reduce heat losses in winter and avoid unwanted heat gains in summer. Heating consumption would descend to 9.53 kWh/m^2y if adopting this solution. Similar results may be achieved with other mobile devices, such as mobile Venetian blinds.

This measure can also help avoid temperature peaks during intermediate seasons when HVAC systems should be off, but there might be some overheating risk. Fig. 12 presents monthly indoor temperature in October with and without window shutters (in yellow and blue lines, respectively), suggesting that the effect can go up to a 5 °C difference.

2.2.4. *Temperature profile of the optimized dwelling prototype*

The passive strategies described above allow dwelling prototypes to have low heating consumption and despicable cooling consumption while maintaining optimum indoor conditions. In free-running mode or without thermal conditioning, indoor temperatures would exceed the comfort band only a few hours a year. An admissible value of 10% for overheating risk is achieved when considering the EN15251 standard

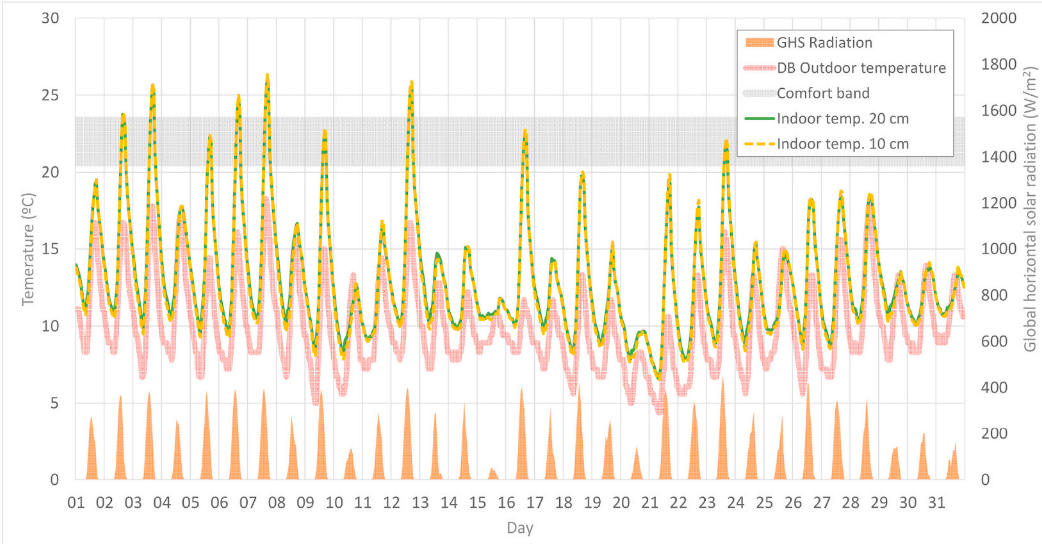

Fig. 9. Thermal insulation thickness analysis. Monthly indoor temperature in January.

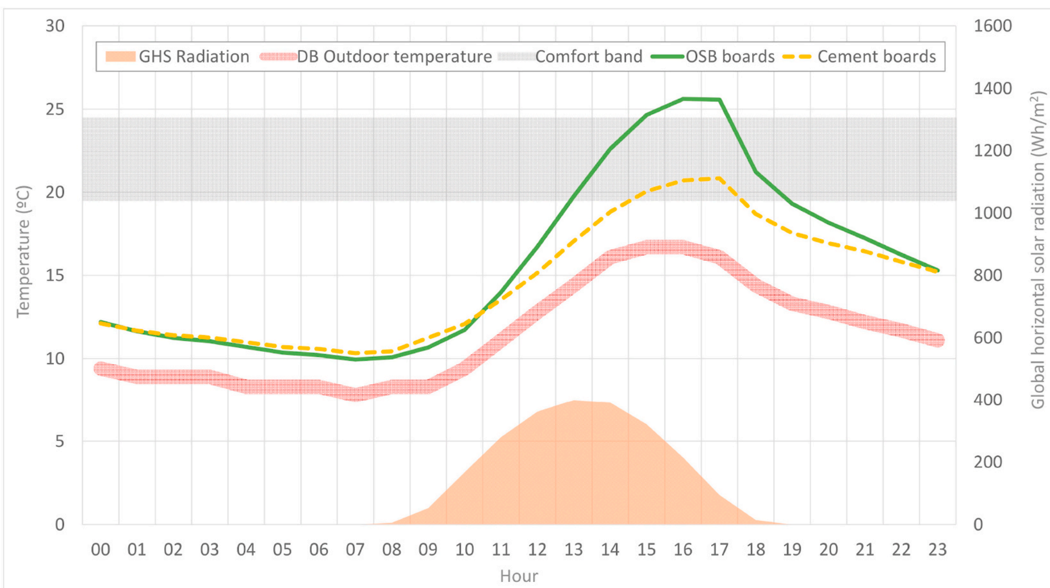

Fig. 10. Indoor finishes with thermal inertia. Daily temperatures in winter.

approach (6,02%), but it is exceeded when accounting for the Passivhaus limit of 25 °C (14,04%). As suggested by Oliveira [6], it is plausible to consider higher maximum temperature limits to adopt the Passivhaus concept for buildings in southern European warm climates. Table 3 shows the main characteristics of the optimized dwelling prototype.

Monthly temperatures show light punctual temperature peaks in winter (Fig. 13) and drops in summer (Fig. 14) that can be easily managed by altering ventilation rates and solar shading schedules. These parameters have been set to fulfill the whole season requirements, but finer adaptability to monthly or weekly outdoor conditions can be performed. Indoor thermal variation is now clearly smoother than the outdoor temperature profile, evidencing the improvement of the building's indoor thermal stability.

Daily temperatures in the winter signify the building's effective use of solar access and the effect of the variable ventilation regime. Days 12, 14, and 15 of January were chosen to represent sunny, semi-cloudy, and cloudy days, respectively, based on global horizontal solar radiation values. Day 12 is considered sunny, and thermal comfort is achieved in free-running conditions. Heating is necessary for several hours on day 14, with semi-cloudy conditions. Thermal comfort is entirely dependent on active heating on day 15, with very low solar radiation. Although, the indoor temperature exceeds the comfort band by less than 1 °C during one-third of the day.

During summer, the dwelling is within the indoor thermal comfort temperature range almost every time in free-running conditions, showing daily variations much smaller than the external temperature. Days 17, 21, and 31 of August were chosen to represent typical, hot, and cloudy days, respectively, based on the values of the outdoor temperature and the global horizontal solar radiation.

Solar shading and natural ventilation guarantee indoor temperatures between 22.62 °C and 26.51 °C, with the HVAC off on the 17th of August, which is considered a typical summer day. The 21st of August is considered a hot day with an outdoor temperature of 29.4 °C. The indoor temperature slightly exceeded the comfort band under free-running conditions, but it was still lower than the outdoor temperature, thus avoiding overheating. Finally, on the cloudy day of the 31st of August, the indoor temperature would stabilize on the comfort band's

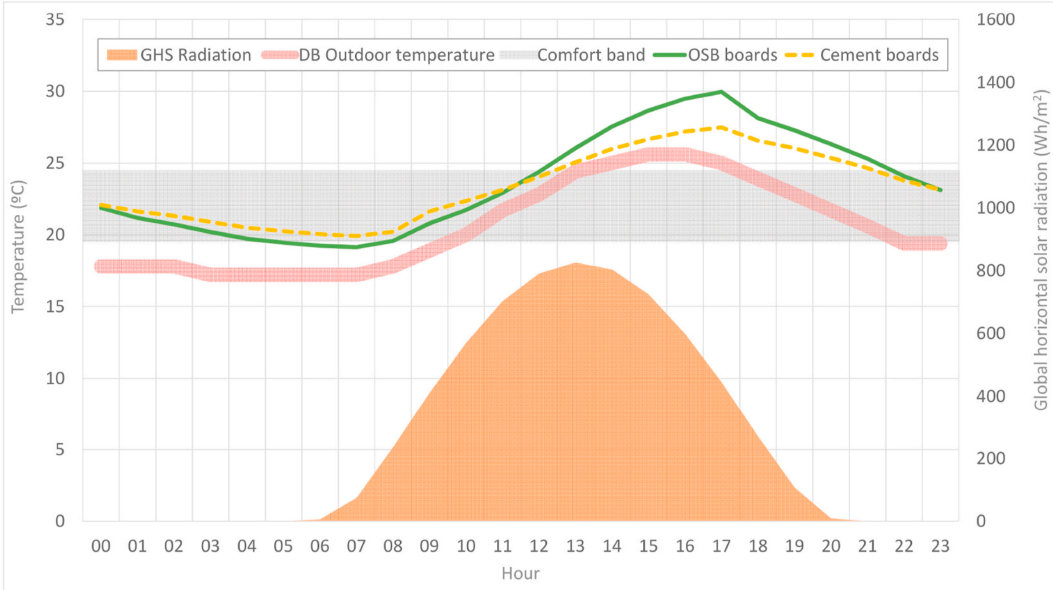

Fig. 11. Indoor finishes with thermal inertia. Daily temperatures in summer.

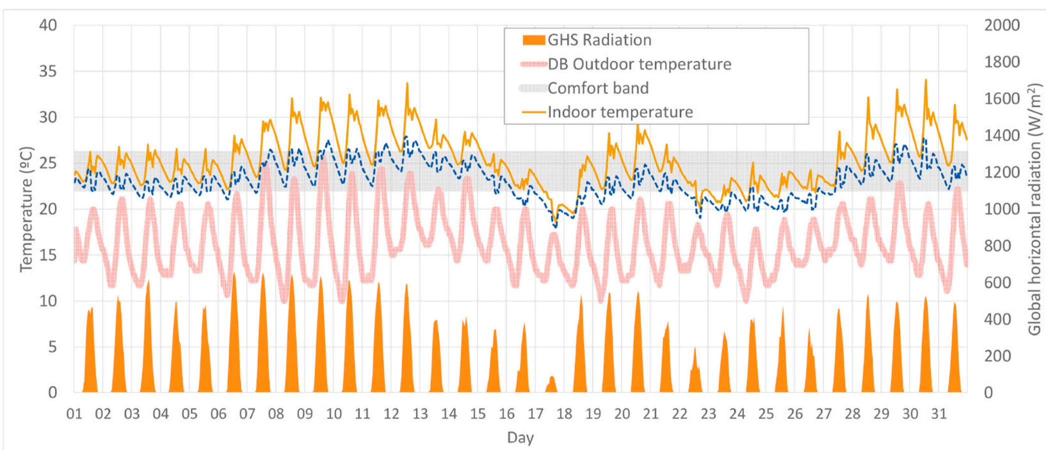

Fig. 12. Use of window shutters in intermediate season. Temperatures in October.

Table 3
Main characteristics of the optimized dwelling prototype.

WWR (%) South North East West	Insulation thickness (cm)	Glazing U-value (W/m^2°C)/SHGC	Overhang length (cm)	Indoor finishes density (kg/cm^3)/Thickness (mm)	Temperature setpoint in January/in August (°C)	Ventilation rate in January/August (l/s)	Mobile devices
94.21 20.10 9.92 6.61	10	1.36 0.45	120	1200 18	19.6 23,1	99 132	Window shutters

lower level. Minimum values at the beginning and the end of the day can be easily addressed by adjusting ventilation rates. Further improvement may also be achieved by preheating and precooling air inlets using heat recovery systems.

3. Results and discussion

With this pack of cumulative measures, the dwelling prototype has a consistent environmental performance, meeting energy consumption and indoor comfort targets. The impact of a particular measure can be affected by all the other aspects. Therefore, other combinations may be equally effective and have different economic, technical, and functional implications, responding to agent skills, user preferences, and budgets. Further details and impact curves on the most relevant aspects are undertaken in section 3, considering economic significance. The goal is to elaborate a guideline to assess dwelling design that may serve a broader scope of project requirements.

Graphs in section 3 show energy consumption variation (heating in orange line and cooling in blue line), according to the variation of a de-

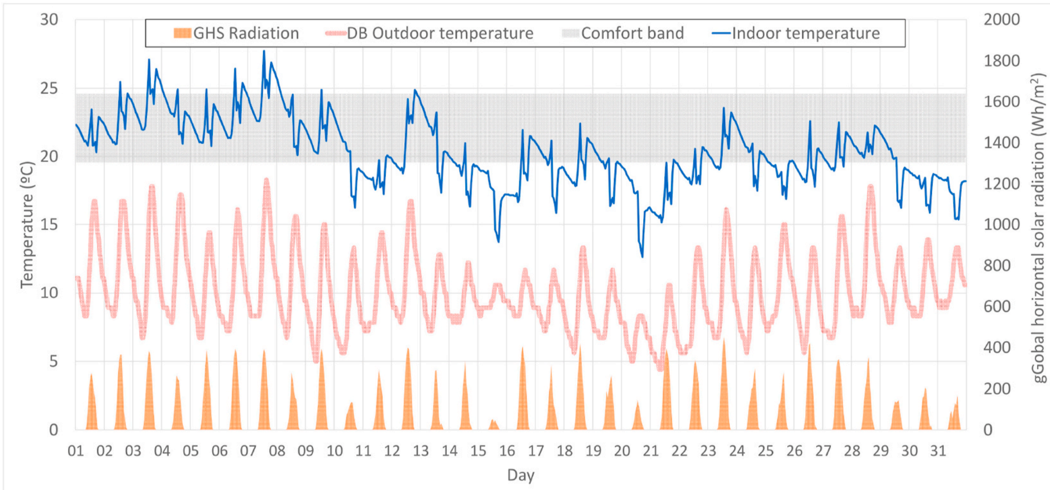

Fig. 13. Monthly temperatures in January.

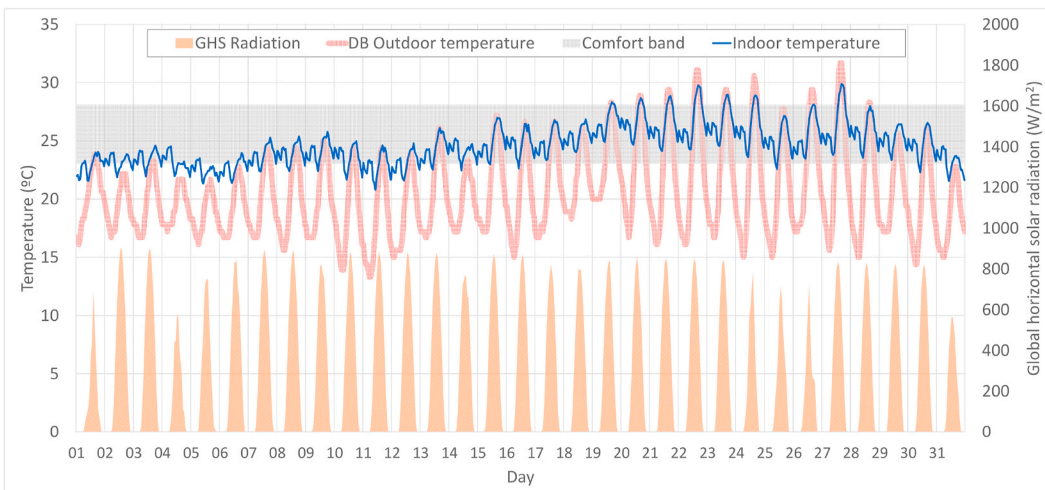

Fig. 14. Monthly temperatures in August.

sign parameter in the horizontal axis, related to its cost (green line), based on the CYPE price construction database.

3.1. Insulation thickness

The insulation thickness determines the envelope thickness, affecting the building cost and useful building surface. Precise calculation of insulation thickness has economic and functional advantages. Fig. 15 shows the energy consumption variation as a function of the facade insulation thickness from 2 cm to 30 cm, from left to right in the horizontal axis.

Reduction of heating consumption is abrupt for 2, 4, and 6 cm, remarkable for 8 and 10 cm, when the energy target is reached, and smooth from 12 to 30 cm, when the increment of 2 cm impacts less than 1 kWh/m^{2}y. The insulation thickness of the initial prototype, which is 20 cm, implies a heating load reduction of 3.93 kWh/m2 y and an increase in the cost of 58%. The effect on cooling loads is negligible.

Analysis of the insulation thickness of other construction elements can be interesting for further improvement. According to Oliveira [6], the maximum thickness should be on the roof insulation, regardless of the location. In surfaces with low heat losses, a minimum level of insulation may be beneficial. Santos [34] explained that low thermal insulation on the ground slab could reduce summer indoor temperatures in buildings located in CSB climate regions.

3.2. Window glazing type

The window glazing type has a significant influence on both the environmental performance and the building cost. The balance between the U-value (i.e., determines the heat loss) and the SHGC (i.e., defines the radiation that enters the indoor space) are vital aspects to consider in selecting the most appropriate window glazing type.

Fig. 16 illustrates annual energy consumption (heating in orange line and cooling in blue line) according to seven window glazing types (among them, the three types considered in section 2.1), from lower to higher performance (from left to right in the horizontal axis), related to their cost (green line), as described in Table 4. The glazing type varies from 4 mm uncolored single glazing (with a U-value of 6.81 W/m^2 $^{\circ}$C and SHGC 0.25) to triple glazing with argon gaps (with U-value 0.36 W/m^2 $^{\circ}$C and SHGC 0.45). All windows include aluminum frames with thermal bridge breaks.

Of these seven types, only the three most thermally resistant meet the efficiency target: window glazing type 1.1 (double low-e coating glazing 8 + 8/10/4), type 1 (double glazing argon filled, as used in the prototype), and type 0 (triple glazing argon filled). However, economic differences are low. Similar results are found in studies on lightweight constructions in moderate climates, such as [6], where double to triple glazing is strongly advised for North and South orientations, in addition to a strongly insulated opaque envelope.

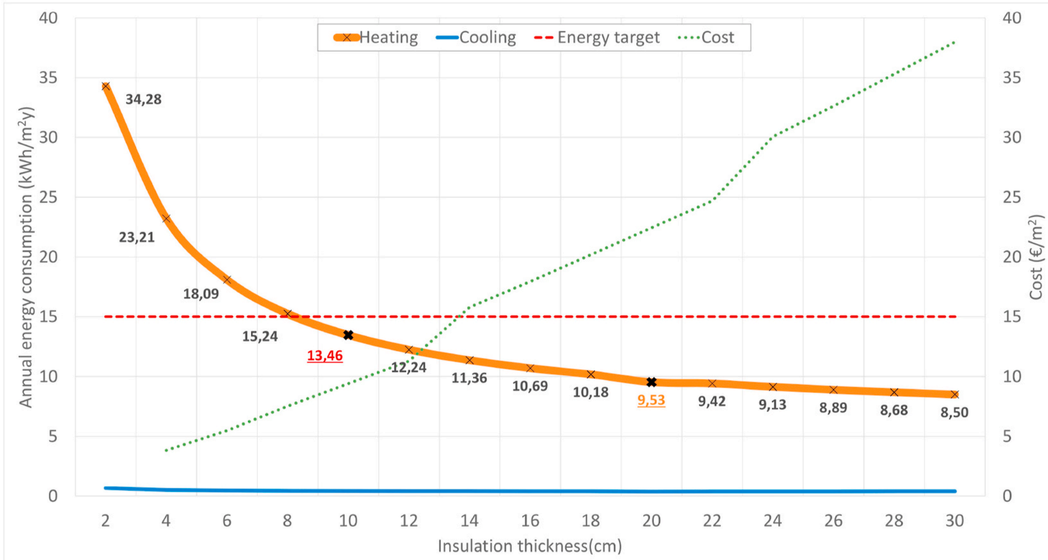

Fig. 15. Parametric study of facades insulation thickness.

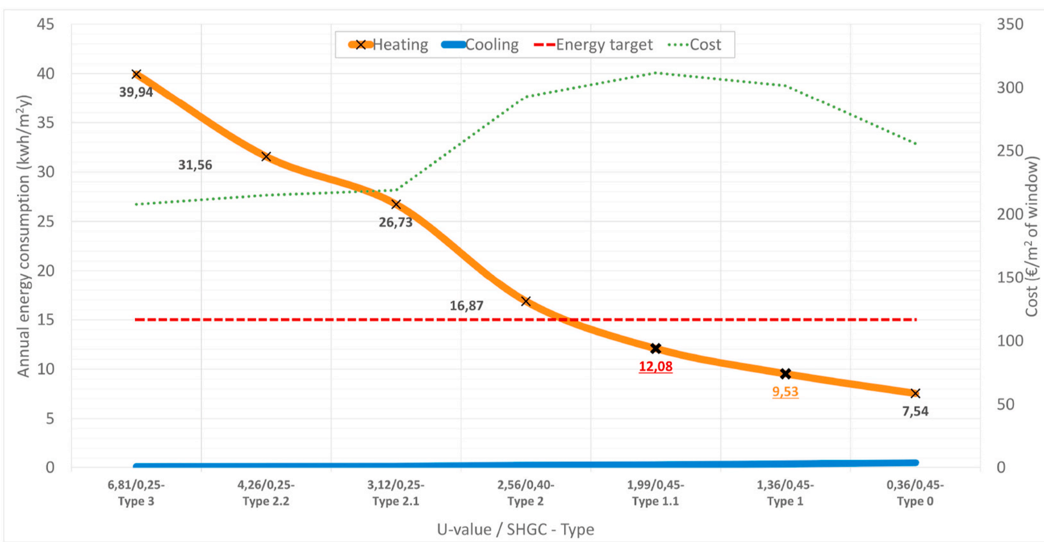

Fig. 16. Parametric study of window glazing type.

Table 4
Window glazing types characteristics.

	Type 0	Type 1	Type 1.1	Type 2	Type 2.1	Type 2.2	Type 3
U-value (W/m^2°C)	0.36	1.36	1.99	2.56	3.12	4.26	6.81
SHGC	0.45	0.45	0.45	0.40	0.25	0.25	0.25
Glass specifications	Triple argon filled	Double argon filled	Double low-e	Double low-e	Double	Single	Single
Glass thickness (mm)	6/14/4/14/4	8 + 8/10/4	8 + 8/10/4	3 + 3/6/4	4/8/4	6	4

3.3. Window to wall ratio (WWR)

Opening size also has a large effect on building heat gains and losses. The optimum balance between transparent and opaque facade surfaces varies with latitude and depends on window solar shading and glazing. In this section, the South Facade's opening size influence on building energy consumption is examined for Pontevedra. Six WWRs, from 94% (the maximum South opening size, characteristic of the optimized prototype) to 14%, are analyzed.

Due to the window shutter's insulation effect, openings lessening leads to a reduction in solar gains, but it does not involve a reduction in heat losses. Therefore, heating consumption boosts progressively (orange line, named "Prototype"), while the facade cost decreases. However, in a no-window shutter scenario (with thermal inertia in the brown line and without thermal inertia in the red line), it does involve a reduction in heat losses. That is why heating consumption remains steady until a WWR of 50% (Fig. 17).

If the same analysis is undertaken considering lower thermal resistant window glazing, such as type 2 (U-value 2.56 W/m^2°C and SHGC 0.40), the reduction in heat gains is larger than the reduction in heat losses so heating consumption decreases with high WWR (yellow line). For medium WWRs (46% and 30%), the decrease in heat gains reduces heat losses and heating consumption boosts. In all these scenarios, cool-

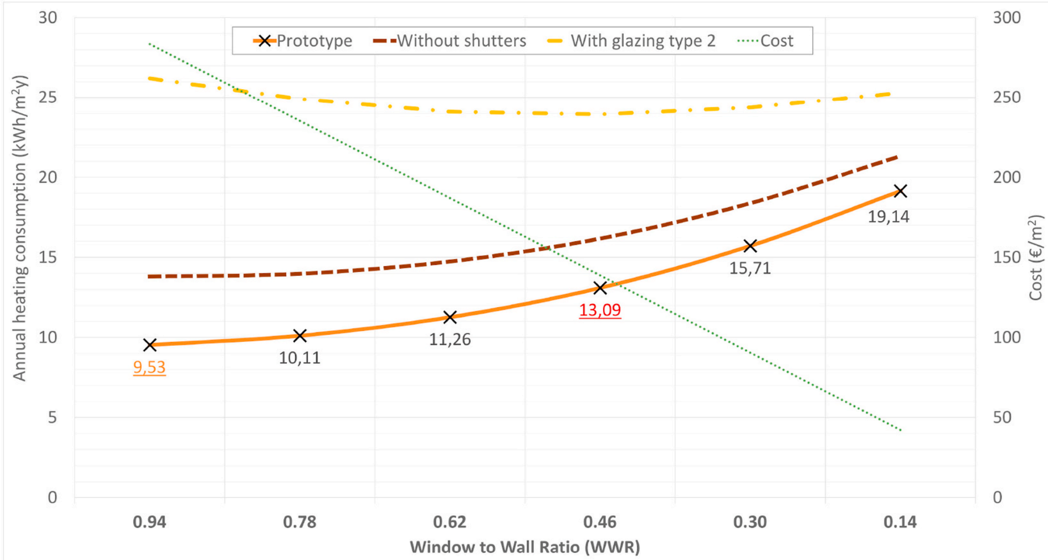

Fig. 17. Parametric study of openings size in the South facade.

ing loads remain practically constant, except for the one considering no inertia.

3.4. Solar shading

Overhang length is a crucial aspect of dwelling aesthetics and structure. If the building has vertical solar shading, such as window shutters, long overhangs provide no environmental benefits. Specifically, the optimized prototype has overhangs on the South facade 120 cm long.

Fig. 18 represents the annual energy consumption related to the overhang length variation in the south facade. Heating loads can diminish by 41% in the absence of overhangs while cooling loads would increase for overhang lengths equal to or less than 60 cm. The optimum overhang length for this building located in Pontevedra is approximately 30 cm, as the total energy load would be at a minimum (7.78 kWh/m^{2}y).

Similar effectiveness of solar protection by horizontal overhangs was proven by Ref. [34], achieving high indoor thermal stability in southwest-oriented bedrooms during summer. Although heat gains are lower during winter, the annual balance is considered extremely positive since that is the parameter with the highest impact on the results.

3.5. Indoor finishes with thermal capacity

Thermal inertia is very important for lightweight constructions, especially for summer comfort [34]. Effectiveness on smoothing indoor temperature profiles has been commented above. There is also a specific effect on energy savings. Notably, the use of cement board on all indoor surfaces of the optimized prototype entails energy savings of 13.91% compared to oriented strand board (OSB), although economic differences are relevant. Considering that the choice of indoor finishes has constructive, economic, and aesthetic implications, the partial use of cement boards is also explored (Table 5). The floor and ceiling options offer the right balance between energy savings (orange and blue bars) and cost (green line). Finally, board thickness has a particular impact on energy efficiency, although the increment in cost is considerable.

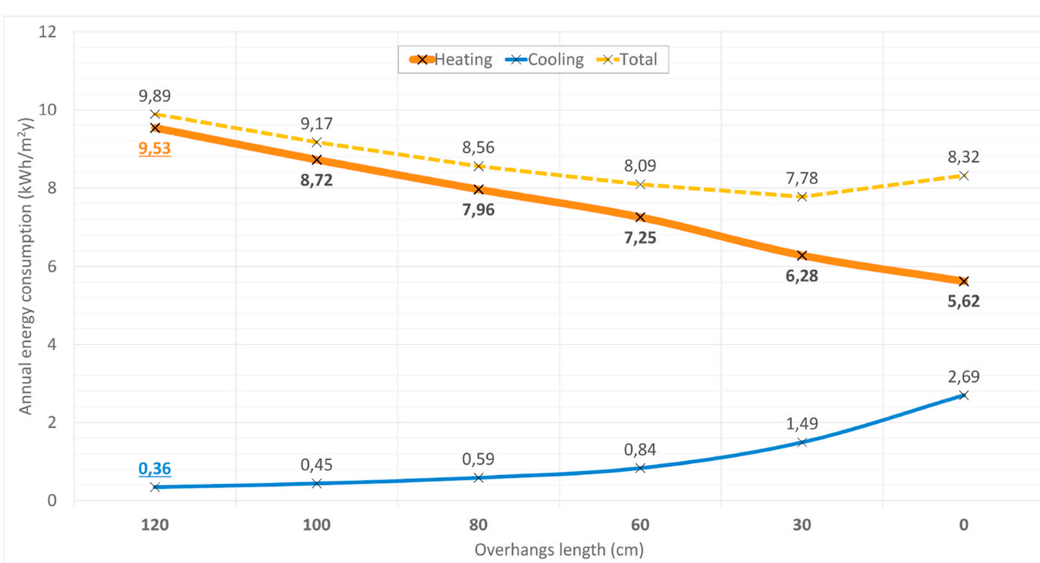

Fig. 18. Parametric study of overhang length.

Table 5
Indoor surfaces with thermal capacity finishes.

Surfaces with indoor finishes of cement boards	None	Floors	Walls	Floors and walls	Walls and ceilings	All
Annual heating demand (kWh/m^2y)	11.07	10.65	10.59	10.29	10.08	9.53
Annual cooling demand (kWh/m^2y)	0.72	0.57	0.55	0.46	0.47	0.36

This measure can be categorized as "sensible storage" because the indoor finishes have a continuous temperature change over time. Further energy savings may be achieved by applying hybrid adaptable thermal storage (HATS), so the building can adapt better to the variation in outdoor conditions throughout the year. According to the studies carried out by Ref. [34], HATS may reduce energy demand up to 35% compared to a conventional permanent high thermal concept in climates that show a distinct temperature difference between the seasons.

3.6. Adaptability to other contexts

The guideline described in section 3 offers a specific scope on the environmental design of liner tray dwellings on an ideal plot in the climate of Pontevedra. However, the construction system's value relies on adapting to different climatic conditions and urbanistic requirements, maintaining environmental quality.

3.6.1. Climate conditions

Three locations at three latitudes and very different climatic conditions were selected: Madrid, Sevilla, and Berlin.

Madrid has cold winters and hot summers and sharp seasonal differences (Energyplus weather file ESP_Madrid.082210_ SWEC). Changes in overhang length to 30 cm and window glazing type 0 (triple argon filled with U-value 0.36 W/m^2 °C and SHGC 0.45) allow annual energy consumption targets to be reached, although heating loads are slightly larger than cooling loads (14.51 kWh/m^2y and 9.38 kWh/m^2y, respectively).

Sevilla has sweltering summers and mild winters (EnergyPlus weather file ESP_Sevilla.083910_IWEC). Night cooling is an effective strategy, as it increases ventilation rates at night and avoids air exchange at midday in hot months. The energy accumulated on the indoor surfaces during the night, when the lowest temperatures are registered, is reirradiated to the indoor spaces during the day. The use of window shutters for solar protection at midday is also useful. As a result, cooling loads can be maintained at 11.64 kWh/m^2y. Heating loads in this climate are just 1.34 kWh/m^2y.

Berlin has severe winters and warm summers (EnergyPlus weather file, DEU_Berlin.103840_IWEC). Several changes are needed to fulfill energy efficiency requirements: overhangs length of 30 cm, window glazing 7, insulation thickness of 36 cm, and adjustments in temperature setpoint and ventilation schedules. In this scenario, heating loads would be 14.69 kWh/m^2y, and cooling loads would be 7.93 kWh/m^2y.

Table 6 summarizes these results, listing the dwelling prototype's annual energy consumption in these three locations compared to Pontevedra, all of which are inferior to 15 kWh/m^2y. This analysis shows that window glazing, thermal insulation, and solar shading are key features when addressing adaptation to different outdoor conditions. The work developed by Oliveira [6] also gives great importance to window glazing and thermal insulation according to climate severity compared to other input parameters.

Table 6
Adaptability to different climate contexts.

	Pontevedra	Madrid	Sevilla	Berlin
Annual heating demand (kWh/m^2y)	9.53	14.51	1.34	14.69
Annual cooling demand (kWh/m^2y)	0.36	9.38	11.64	7.93

3.6.2. Urbanistic requirements

The main urbanistic aspects, such as orientation, solar access, views, and access, are not always fully compatible. The complexity and variety of building plots demand compromise solutions to achieve a satisfactory balance.

Significant openings in the south facade, moderate openings in the north facade, and minimum openings facing the east and west are simple schemes that help maximize solar gains and minimize heat losses. However, other schemes can respond better to site particularities, so WWR variation should be adjusted accordingly. This section explores the energy curves of several WWRs in all facades to obtain a view of the tolerance of opening size.

The choice of WWR responds to the proportional size variation of the initial openings. More satisfactory results may be achieved with smaller WWR intervals. Simulations are performed without considering window shutters, so a window balance of heat gains and losses can be noticed.

Simulations show that only the scheme described above, or very similar schemes, allows fulfillment of the energy target in the location of Pontevedra (Fig. 19). However, there is a broad scope for opening variation in all orientations, as long as solar gains in the South facade are kept relatively high (approximately 62%) and windows are insulated in coldest hours through the use of shutters, as shown in Table 7.

Specific reductions in South openings (34%) and enlargements of North openings (49%) can be carried out without compromising the energy target. South openings are essential for sufficient solar access, but they can be reduced from 94% to 62% with minimum impact on heating loads (less than 1 kWh/m^2y). North opening variation regularly affects heating loads, decreasing by approximately 1 kWh/m^2y for each WWR. However, variation between 30% and 14% has a lower impact (0.40 kWh/m^2y). Enlargements from 20.10% to 30% have a minimum impact on heating loads.

Enlargement of east and west openings hinders achieving a heating target in a similar amount for all WWRs. For approximately WWR 46% or more, the impact also affects cooling loads. East and west opening variations have minor effects on heating loads, but they substantially impact cooling loads and summer indoor comfort. If needed, further enlargement of these openings can be undertaken without increasing heating loads, as long as they have shutters to assure energy efficiency in winter, which are also useful for controlling thermal peaks in summer and mid seasons.

4. Conclusions

This paper studies the passive strategies of the liner tray system Proyectopía for the design assessment of detached housing based on a representative house prototype. The aim is to obtain environmental design guidelines that can be of use to a wide range of project requirements, seeking thermal steadiness and using annual energy consumption as the primary indicator.

Insulation thickness has a direct impact on heating consumption, as it mainly affects heat losses. The energy curve of the insulation thickness of the load-bearing walls and the facades has an exponentially decreasing profile with a bend point of 8 cm, while the economic increase is linear. The energy target is attained with 10 cm thickness. A further increase in the façade's thermal resistance causes a minor effect on the energy efficiency, yet it has a relevant effect on the material cost and facade configuration.

Window glazing is a delicate aspect, as it strongly affects heat losses and heat gains. The energy curve of the window glazing type has a linear profile for the first four types analyzed, and it becomes less steep for

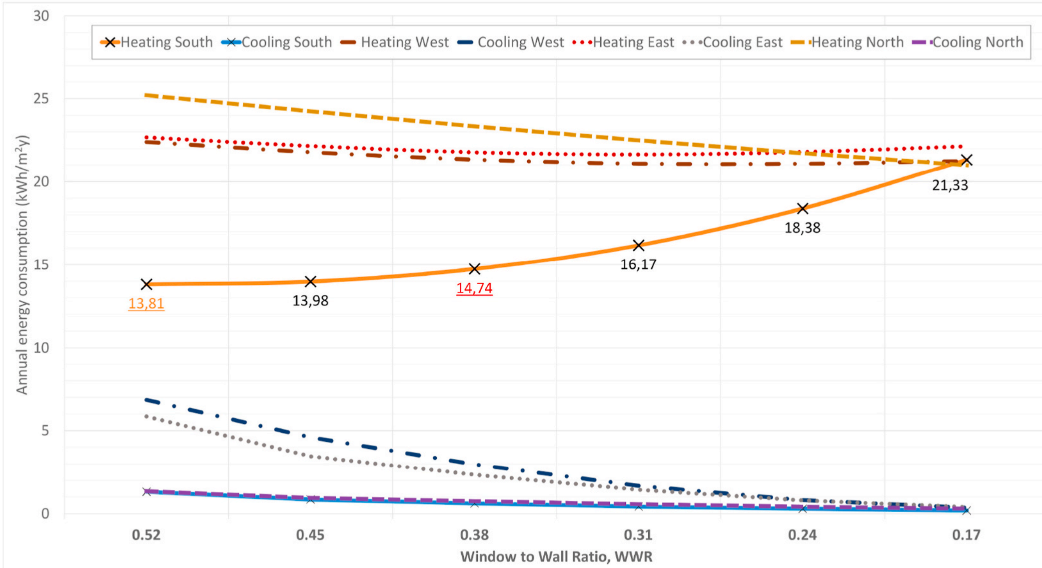

Fig. 19. Impact of WWR variations in all facades.

Table 7
WWR range variation (%).

South	North	East	West
62–94.21	20.10–30 (if shutters)	9.92–46 (if shutters)	6.61–46 (if shutters)

the last three types. However, the cost line increases abruptly from type 2.2 to type 2. The energy target is achieved with window glazing type 1.1, U-value of 1.99 W/m^2 °C, and SHGC of 0.45.

The opening size is a crucial characteristic of energy consumption that strongly impacts facade design and building cost. With small openings in north, east and west orientations (WWR 20.10%, 9.92%, and 6.61%, respectively), there is scope for opening size variation in the south facade. The glazing surface can be decreased to 46%, reducing the window cost if window shutters and indoor finishes with thermal capacity are used. If there are no window shutters, openings in the south facade should not decrease by 62%.

Solar shading is essential for maintaining indoor comfort in lightweight buildings. Overhangs are fixed devices that provide benefits all year long, whose length should be 120 cm in the south facade to avoid thermal peaks with high WWR in the location of Pontevedra. Window shutters are mobile shading devices that can also provide thermal insulation. In combination, the overhang length can be decreased to 30 cm. The performance of intermediate solutions or the use of other shading devices can be drawn from these calculations.

Indoor finishes with thermal capacity are very useful in LSF construction, as they help smooth indoor temperature profiles. Thermal peaks can be reduced at 5 °C, and heating consumption can be lowered by 13.91% with cement boards in floors, walls, or ceilings. Other alternatives to increasing building thermal mass can be equally effective, although technique and economic aspects should be considered.

The validity of the passive strategies depends on the site conditions and construction systems. The adaptability of the Proyectopía system to different climates was tested by modifying the parameters studied above. The increase in thermal resistance and winter solar gains have proven to be effective strategies in colder climates. Night cooling and intensive solar shading can be advantageous in adapting to hotter climates.

In addition to climate needs, the particularities of the building site, such as views, plot shape, or access, can affect building orientation and facade design. The ideal scheme of moderate window opening in all orientations except in the South may be inconvenient in many project locations, so the tolerance range of WWR has been analyzed. Six WWRs were calculated by periodic reduction of window openings. More accurate outcomes may be obtained by using shorter variations. If using window shutters, there is a broad scope for opening variation in all orientations once solar gains are assured by approximately 62% WWR on the South facade. Without window shutters, heating consumption would surpass the energy target if WWRs are altered. Heating loads increase when openings in the North Facade exceed approximately 30% while cooling loads suffer exponential growth once openings in the East or West Facades reach approximately 46% of the surface.

Innovation in housing construction is decisive for the spread of efficient, affordable homes. However, energy efficiency cannot be achieved without good environmental design, despite the construction quality. Design guidelines based on parametric studies can be a reliable and time-saving tool for projects of detached houses, which require adaptation to different requirements and plot locations.

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CRediT authorship contribution statement

Patricia Linhares: Conceptualization, Methodology, Software, Writing – original draft, Writing – review & editing. **Víctor Hermo:** Validation, Investigation, Resources. **Carolina Meire:** Visualization, Supervision, Project administration.

Declaration of competing interest

The authors declare that they have used the liner tray described in the research paper in the design and construction of detached houses as a result of the work they develop in the company Proyectopía SL.

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